SELF HEALING DISTRIBUTION NETWORKS USING SMART CONTROLLERS

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ABSTRACT

Major power system disturbances and outages have a significant economic and social impact and the security of supply becomes a more and more important issue. Hence outage times should be as short as possible. Smart grid technologies such as self-healing networks can help in reducing the outage times after a disturbance. In this paper the principle and implementation of a self-healing grid for cable networks is discussed. Both technical and organizational issues will be addresses.

INTRODUCTION

Economic growth and an increasing population translate to more energy demand. This situation, coupled with strict regulations on the quality and reliability of supply mounts increasing pressure on the distribution network operators to keep the network at the best possible state. While huge investments are already being made on replacing the aging infrastructure to prevent equipment failure, the chance of failure however, cannot be completely eliminated. For the faults that can't be prevented, it is therefore necessary to minimize the impact by keeping the outage time as short and the affected customers as few as possible.

In order to minimize the fault outage time the Dutch distribution operator Stedin has started a project to adapt automation to their distribution grid. The first phase of the project consists of installing intelligent fault passage indicators while the next two phases utilize more advanced techniques such as remote controlled ring main units and a complete self-healing distribution feeder. Self-Healing systems have a technical impact but also an organizational impact. Change management and other organizational aspects will be described in this paper.

Pilot projects

Currently, there are several examples of a self-healing distribution grid. For instance in Fortum Oy, Masala Finland where a distribution grid consisting of mainly overhead lines is automated [1]. In this example the distribution feeders are divided in four zones which are equipped with intelligent fault passage indicators (FPI), reclosers, and switch disconnectors. The logic is programmed in local Remote Terminal Units (RTU). In these types of grids the main type of faults are temporary.

In the Netherlands, the distribution grid consists of cables which mean that only permanent faults occur and these faults cannot be solved by stand-alone automatic reclosers. The self-healing grid pilot which Stedin has developed is based on a software restoration routine which runs at several remote terminal units. These units communicate via a GPRS network and execute fault location, isolation and restoration (FLIR) steps automatically. The principle of this pilot will be discussed in detail in the subsequent sections.

Automatic FLIR schemes can be implemented with several different architectures. Fully centralized schemes use a Distribution Management System (DMS) that has a complete picture of the network topology. Local centralized schemes use intelligence at master controllers each of which communicates with a limited number of slave devices.

The scheme described in this paper is a fully decentralized architecture where the intelligence is distributed between several nodes. The FLIR algorithm uses messages passed between a number of Smart Controllers. The communication architecture mirrors the electrical network which makes it easy to add or remove nodes.

AUTOMATED NETWORK

For the Stedin self-healing grid pilot a MV (23kV) network in the city centre of Rotterdam was selected. This network consists of 33 secondary substations connected in a ring. It is operated as two radial feeders by creating a normally open point. See figure 1.

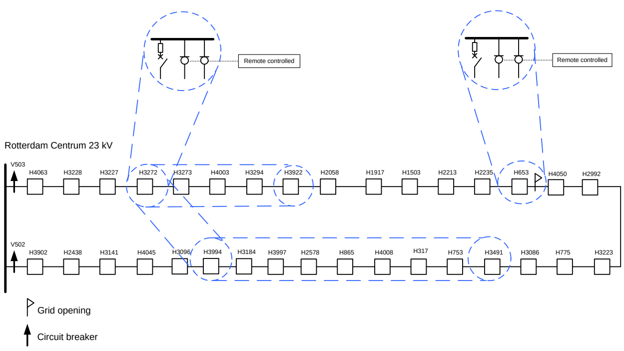

Figure 1: *MV-network for the self-healing grid pilot*

Distribution automation

Ideally all 33 secondary substations would be fitted with automation equipment but this is expensive, A cost-effective solution was to select five substations so that the ring was divided into two feeders each with three sections each with approximately equal cable lengths and numbers of customers.. These secondary substations are equipped with distribution automation which consists of:

- A motor drive to operate the load break switches
- A RTU in which the logic is programmed
- Fault Passage Indicators(FPI)
- Voltage presence detection

The circuit breakers V502 and V503 in the primary substation are automated with different equipment:

- A protection relay to trip the circuit breaker
- A SCADA RTU for monitoring and control
- A Self-Healing RTU controller to initiate the FLIR sequence and reclose the breaker.

Figure 2 gives a more detailed overview of the distribution automation in the secondary substations.

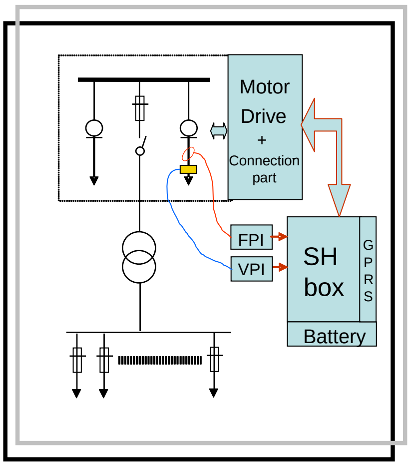

Figure 2: *Detailed overview of the distribution automation*

In this figure a SH-box is depicted which consists of the RTU including a battery and a GPRS modem for communication purposes. The fault passage status is calculated within the RTU using a current measurement on the incoming and outgoing cables. Finally a voltage presence indicator is capacitively connected to each cable to detect if the cable is energized.

Communication infrastructure

The daily operation of a power system relies more and more on communication. For instance, remote switching operations, data collection for the historical information system and state estimation are functions which need a communication infrastructure. Stedin has setup their own communication infrastructure which means that for primary substations an own TCP/IP network consisting of fibre optic and copper cables. For the secondary substations GPRS/UMTS will be used from a selected telecom provider. A generic overview of the communication infrastructure for secondary substations is shown in figure 3.

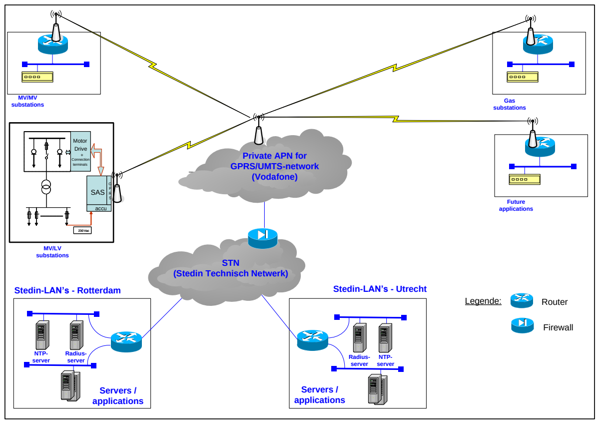

Figure 3: *Generic overview of the Stedin communication infrastructure*

For this pilot project the mutual communication between the RTUs of the self-healing grid takes place via the GPRS network while the communication to the circuit breakers in substation Rotterdam Centrum and the EMS takes place via the fibre optic network.

GENERAL PRINCIPLE OF THE SELF-HEALING GRID

The idea behind the self-healing grid is to automate the manual fault restoration procedure. As described above, a small number of substations are fitted with automation equipment. The Self Healing system will rapidly restore 2 out of 3 feeder sections (and customers) automatically but leave one feeder section isolated. Location of the actual fault within this section and restoring supply to the remaining customers will be performed using the traditional manual process.

The self-healing grid is able to handle cable faults as well as busbar faults in the RMU. In case of two faults at the same time the self-healing grid is able to restore the power as much as possible.

There are two main principles for the fault location and isolation algorithm:
a) If the fault detectors indicate that the fault is located between two nodes, then this is due to a cable fault and switches are opened in both nodes.
b) If the fault detectors indicate that the fault is located within a node, then this is probably due to a fault at a cable termination at the RMU. In this case, opening switches within the node will not guarantee that the fault is isolated. The system therefore opens (or leaves open) switches in the two neighbouring nodes.

The algorithm also had to take into account other features:
Safety: when any node is put in local mode, the self-healing

scheme is automatically disabled at all the other nodes;
Robustness: if a switch fails to operate to isolate a fault, then the system will try the next switch;
Fault-tolerance: handle missing fault passage indications.

Node definition

In this restoration procedure the faulted cable section is isolated by opening two load break switches. The healthy sections are re-energized by closing the normally open point or the circuit breaker. This has led to the definition of a two types of nodes:

1. Breaking nodes
2. Making nodes

The breaking nodes are used for isolating the faulted component while the making nodes are used for re-energizing the MV-network. The controllers at each location are configured with the appropriate node definitions as shown in figure 4. For simplicity the secondary substations between the controllable substations are not shown. The blue dotted lines indicate communication channels between the various SH-boxes.

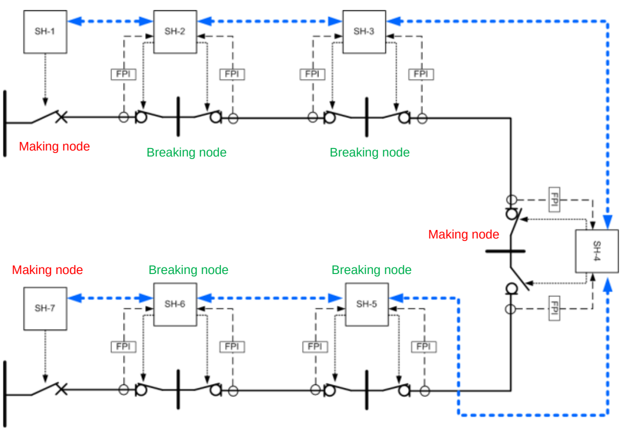

Figure 4: *Assignment of the breaking and making nodes*

FAULT LOCATION AND ISOLATION ALGORITHM

The sequence is started when a controller at the primary substation detects that the protection relay has operated. The algorithm works in two phases. The first phase is the "upstream isolation" phase. Each node analyses if the fault is located upstream of itself, and if necessary isolate it. The second phase is the "downstream isolation" phase. Each node analyses if the fault is located downstream of itself, and if necessary isolates it.

Phase 1

During phase 1, messages are sent "downstream" from the feeder CB node via the Breaking Nodes to the Making node. As each Breaking Node receives a message, it analyses its own local fault passage indicators to find out if the fault is upstream of itself. If so, it will open one of its switches to isolate itself from the fault.

If a Breaking Node successfully isolates the fault, then it will forward the message to the Making Node with the status "Fault Upstream and Isolated". If this status is received by the Making node, it will close the normally open switch.

For example, if there is a short circuit between SH 2 and SH 3 as shown in figure 4, then SH 1 will initiate the sequence. During the first phase SH 3 will open its upstream load break switch and SH 4 will close the normally open switch.

Phase 2

During phase 2, a second set of messages are sent "upstream" from the Making Node via the Breaking Nodes back to the feeder CB node. During this phase, each Breaking Node will complete its analysis of whether the fault is downstream of itself. If so, then it will open a switch to isolate on the upstream side of the fault.

If a Breaking Node successfully isolates the fault, then it will forward the message to the CB Node with the status "Fault Downstream and Isolated". If this status is received by the CB node, it will re-close the breaker.

For the example of a short circuit between SH 2 and SH 3, during the second phase SH 2 will open its downstream load break switch and then SH 1 will reclose the breaker.

At the end of the cycle, only the feeder section between SH 2 and SH 3 is still de-energized. The status of each node is sent to the control centre which can send a repair crew directly to faulted feeder part.

The complete cycle of the self-healing grid takes less than one minute depending on the number of switching operations required. Hence the majority of the connected customers experience a power outage of one minute. In comparison with an average outage time of two hours this is a big improvement.

LESSONS LEARNED

Stedin has started this pilot with the objective to gain technical experience in realizing a smart grid solution. A second, equally important, objective is to gain organizational experience in having these types of solutions in the grid. In this section these two objectives are addressed.

Organizational issues

Smart grid solutions not only have an impact on the behaviour of the network, it also affects people which encounter the changing behaviour of the grid. In this paper a self-healing grid is discussed which alters the fault handling and restoration. Maintenance engineers and operators of the control centre have to adapt fault handing and restoration procedures that have been used for more than thirty years. To obtain the needed paradigm shift, people have to be informed in an early stage of the project. Key issues are safety, active participation and confidence in the solution. Stedin has addressed these issues by organizing workshops, road shows and presentations in the various departments which encounters this new technology. Moreover, to gain confidence and experience of the self-healing grid system a setup of the complete system was made in a test environment. A network ring simulator box was built that provides the correct indication of voltage presence as a function of the (simulated) MV load break switches, The simulator box included simulation of the fault currents to trigger the fault passage indicators and simulation of the protection relay trip signal. Maintenance engineers and operators of the control centre were invited to attend the demonstrations and on their request all possible fault scenarios could be simulated and the system reaction could be demonstrated. These demonstrations were necessary and helped a lot in gaining acceptance of the new technology and systems. An overview of the test and demo environment is given in figure 5.

Figure 5: *Overview of the test and demo environment including SH-boxes and network simulator (at the bottom)*

Grid design

Not all MV-grid structures are suitable for the self-healing grid functionality as discussed in this paper. In meshed grid structures various possibilities are available in restoring the network after a network fault. This complicates the software routines and chances on malfunctioning increases. In order to gain full benefit of distribution automation, the automation functions should be incorporated in future grid design. This means that for self-healing grid functionality the ring structure with a single normally open point is preferred. At this moment in the Stedin service area this is not the common grid structure.

During the project it was found out that the local LV-network had a meshed grid structure as well. As a consequence controllable nodes could be bridged by LV-couplings. This is demonstrated in figure 6.

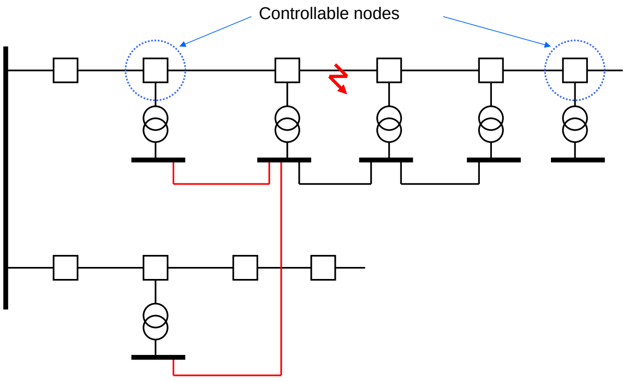

Figure 6: *Example of impact of LV-couplings*

LV couplings in parallel with the MV feeder do not lead to any problems during normal operation. However, LV-couplings between a faulted section and another restored healthy feeder section can energize the fault. This can result in a dangerous situation and should be avoided. Procedures for this are included as part of the manual restoration processes. For automated self-healing the LV couplings must be removed in advance. During the project all LV-couplings were removed in the low voltage network.

CONCLUSIONS

In this paper the principle and implementation of a self-healing grid is discussed. Because the Stedin MV-network consists of cable only the functionality differs from the solutions which are applied in MV-networks including overhead lines. For a successful implementation technical as well as organizational issues have to be addressed. Especially the organizational issues have to be addressed in an early stage of the project. This was done by organizing workshops, road shows, presentations and demonstrations. Besides these issues application of self-healing grids affect the grid design. Ring structured MV-networks in combination with radial LV-networks are most suitable to apply the self-healing grid functionality as described in this paper.

Cyber security was addressed during the project by ensuring that all communication was via private networks, either physical or virtual. It is expected that when the number of smart grid solutions increases this topic needs much more attention.

REFERENCES

[1] J. Ahola, 'A self healing power system for the accurate fault localization and zone concept', *proc. of T&D conference 2012, Amsterdam*